A HIGH-SPEED PARALLEL ADDER

for electronic digital computers

CONTINUED research at the National Bureau of Standards on the logical design of electronic computers has resulted in a method for adding two 53-binary-digit numbers in 1 microsecond. When incorporated into a computer's arithmetic unit, this adder will provide a significant saving in time over the currently used parallel adders in solving long, complex scientific computation and data-processing problems.

The high speed of the adder results from a logical arrangement that permits the simultaneous formation of large groups of "carries," i. e., the numbers that are carried over to the next more significant digital positions in addition problems. The adder was developed by A. Weinberger and J. L. Smith of the data processing systems laboratory. It can be constructed from electronic circuitry similar to that in SEAC, the National Bureau of Standards Electronic Automatic Computer.

In the past, parallel adders have been burdened by the problem of carry propagation. If no carries were present, all the sum digits could be formed simultaneously, in parallel. However, a situation may arise in which a carry in the least significant digit position produces a carry in the next digit position, which in turn produces a carry in the third position, etc. The time required for a carry to propagate from the least to the most significant digit position in this manner is known

as the maximum carry propagation time. It is this time that has generally limited the speed of parallel adders. Previous efforts to reduce the carry propagation time have been directed mainly towards devising means for rapidly transmitting a carry from one digit position to the next.

In the Bureau's method of addition, however, whole groups of adjacent carries are formed simultaneously and independently of each other. An analysis using Boolean algebra techniques shows that it is feasible to generate all carries in a limited number of time periods. Specifically, for a 53-binary-digit adder, all 52 carries are formed in only 3 steps of a 5-step operation.

The complete addition operation is performed in five steps, briefly described as follows:

1. During the first step, each of the two operands to be added is made available in parallel, usually from a parallel memory because of its rapid access.

2. During the second step, the four least significant carries, C_1 through C_4, are generated in parallel from the four least significant digits of each operand. Because the logical gating structure is restricted to a limited number of inputs, not more than four carries can be economically generated during this step. However, the remaining digits of the operand generate an array of auxiliary carries at the same time the true
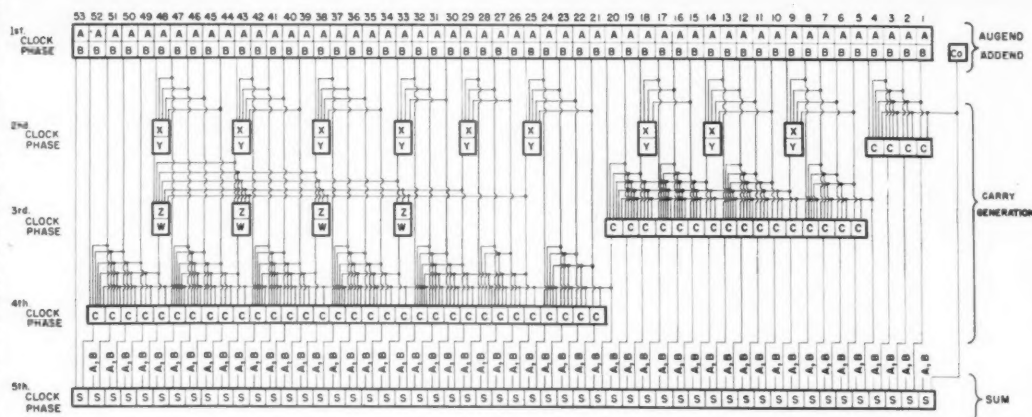
Block diagram of 53-binary-digit parallel adder for electronic digital computers. A, Augend digits; B, addend digits; C, carries; S, sum digits. Auxiliary carries X, Y, Z, and W permit simultaneous formation of a large group of actual carries. Entire addition is performed in five time periods or phases. If SEAC-type circuitry with a 5-phase 1-Mc clock is used, entire addition is accomplished in 1 μsec.

carries, C_1 through C_4, are generated. These auxiliary carries are formed by examining groups of digits in the addend and augend, and permit the subsequent formation of true carries during later steps in the operation. They are formed at certain selected digit positions to check for many of the conditions prerequisite to the formation of actual carries.

3. During the third step, the second and larger group of carries, C_5 through C_{20}, is generated in parallel by means of the appropriate operand digits and auxiliary carries.

Simultaneously, a second array of auxiliary carries is formed from the first array to aid in the subsequent formation of the third and final group of carries.

4. During the fourth step, the last and largest group of carries, C_{21} through C_{52}, is generated in parallel by means of the appropriate operand digits and the auxiliary carries.

5. Finally, after all the actual carries, C_1 through C_{52}, are obtained, all the sum digits are formed in parallel during the fifth step in a conventional manner, each by means of the corresponding addend and augend digits together with the carry from the previous digit position.

The parallel addition process can be demonstrated by first considering the usual method employed in adding two numbers. So far as carries are concerned, the operation of a conventional parallel adder is analogous to the familiar pencil-and-paper method of adding two numbers together. In the following example, decimal digits are chosen for their familiarity (a computer may use only the binary digits, 0 and 1), and have been deliberately selected so that there will be maximum carry propagation. Because of the carry propagation a conventional adder requires a separate

step to determine the carry for each digit position. The step-by-step process would be

$$
\begin{array}{r}
8\,3\,5\,7 \\
1\,6\,4\,3 \\
\hline
0 \\
1 \\
1 \\
1 \\
\hline
1\,0\,0\,0\,0
\end{array}
$$

One time period required for *each* step.

Clearly, each column can be correctly summed independently of the previous column once the carries have been determined. It is this step-by-step process, the propagation of carries down the line of digits, that requires so much time for the addition of a pair of numbers. If it were possible to determine all carries simultaneously, instead of one-by-one, the addition could clearly be performed in much less time. The method developed at the Bureau provides a simultaneous determination of many successive carries. Many carries are generated at once by performing ahead of time a large portion of the switching for many digits to the left, so that during the succeeding time period only a relatively small amount of switching is necessary to form the actual carries. In the above problem, if all the carries were determined simultaneously, the set of carries would be 1 1 1 1 0. The zero in the right-hand column implies that there is no carry from a previous column. The simple addition would now be

$$
\begin{array}{r}
8\,3\,5\,7 \\
1\,6\,4\,3 \\
1\,1\,1\,1\,0 \\
\hline
1\,0\,0\,0\,0.
\end{array}
$$

Because the SEAC-type diode gating and logical circuitry impose a limitation on the number of digits that can be examined simultaneously, not all of the carries can be ascertained in a single step. Instead, the process is divided into three steps, and sets of auxiliary carries are formed together with a number of true carries. However, all true carries can still be formed in $3/5$ μsec. It is the rapid formation of all the carries that gives the adder its high speed. When all the carries are formed, they are logically combined with the appropriate digits in the addend and augend, and the sum is obtained. As each column is now independent of the others, all columns can be added simultaneously and in parallel by the computer.

The adder can be constructed from basic SEAC-type pulse repeater stages. The circuitry consists essentially of three levels of diode gates in an OR-AND-OR (mixer-coincidence-mixer) logical array followed by a transformer-coupled pulse amplifier. The rate at which successive pulses pass through such a stage is determined by the 1-Mc clock frequency. The transit time of a pulse through a stage, however, is much less than 1 μsec. For this reason, the clock pulses are made available in several phases so that successive gating-amplifying units can be timed by clock pulses of successive phases. With a five-phase clock, signals can be dispatched sequentially through five sets of OR-AND-OR gating units in 1 μsec. The five steps of the complete addition operation can therefore be performed during the five successive clock-phase periods occurring in 1 μsec.

For further technical details, see The logical design of a one-microsecond parallel adder using one-megacycle circuitry, *A. Weinberger and J. L. Smith, accepted for publication in the Proceedings of the Western Joint Computer Conference of 1956, and* A one-microsecond adder using one-megacycle circuitry, *A. Weinberger and J. L. Smith, IRE, Transactions on Electronic Computers (in press).*

American Standard Elevator Code Revised

THE American Standard Safety Code for Elevators, Dumbwaiters, and Escalators, sponsored jointly by the American Institute of Architects, the National Bureau of Standards, and the American Society of Mechanical Engineers, is now available in the new 1955 revision. This code has been a source of information for States and cities in formulating their safety and building codes. As a result of improved elevator codes since the first edition of the Code in 1922, the number of elevator accidents in the United States has shown a steady decline although the number of elevators has increased substantially.

For more than three decades the Bureau has taken an active part in the preparation of this important standard. Through surveys of elevator landings equipped with interlocks, the Bureau developed and recommended test procedures to detect some of the commoner weaknesses and causes of failure. As a result of research on hydraulic buffers, test specifications on these safety devices were approved and included in later revisions of the Code. More recent studies of automatic or operatorless elevators have led to the formulation of requirements and standards for safe electrical controls.

The new edition of the elevator Code is the first since 1937 and embodies much new material as well as reorganization of some of the older material. A section on hydraulic elevators has been added, the section on escalators has been revised, and a set of rules governing repairs and alterations added. All engineering formulas, design data, and rules on inspections and tests are now grouped together in separate sections. The section on control has been revised and additional requirements covering automatic operation added. Capacity curves for passenger elevators have been changed to prevent overloading of the car, and minimum allowable unit floor loadings for freight elevator cabs are included. Car-top platforms and bracket-mounted fans in the car are now forbidden. Electrical conduits in the hoistway, other than those that supply power to the elevator machine or to hoistway lighting, are no longer permitted.

Because the misuse of emergency keys for hoistway doors has resulted in many fatal and serious accidents, the new Code prohibits their use. In place of these keys, switches in the hallways at the top and bottom landings are now required. These switches permit the car to be moved for a limited distance at slow speed with the hoistway door open to give mechanics and inspectors access to the top of the car and to the pit.

Increasing in popularity are private residence elevators; such cars are limited to a speed of 40 ft/min and a maximum load of 700 lb and are restricted to service in dwelling units occupied by one family only. The new Code does not require them to meet all of the rules for passenger elevators carrying the general public. For example, pits are not required because their installation usually demands major structural changes in the building; the elevator platform is designed to land directly on the lower floor.

The new edition of the Elevator Safety Code is intended to be adopted by States and municipalities as their local elevator code, which may be part of their building code. It is also intended as a standard reference for architects, engineers, casualty insurance companies, and manufacturers, and as a standard of practice for owners and managers of structures wherever elevators are used. The 1955 revision is available from the American Society of Mechanical Engineers, 29 West 39th Street, New York 18, N. Y. Its cost is $3.50, paperbound, or $4.00 clothbound.

Determination of Resin Content in Plastic Laminates

THE BUREAU has developed a fast yet very accurate method for determining resin in glass fiber-polyester laminates where calcium carbonate is a filler. S. D. Toner of the plastics laboratory has demonstrated that the high, resin-decomposing temperatures employed in the usual test cause calcium carbonate to decompose and thus produce errors in the results. Developed for the Air Force, this test restores the decomposed calcium carbonate to the residue so that the resin content can be more precisely calculated.

Glass fiber-reinforced laminates are being used to an increasing extent in molded parts for aircraft, automobiles, refrigerators, and other products where plasticity, lightness, and strength are required. Plastic laminates have many potential military and civilian applications, but the feasibility and economy of applying these materials to production items depend to a large degree on good quality control and reliable design data. Although inexpensive calcium carbonate fillers may be used advantageously in glass fiber-reinforced laminates, the strength properties of the laminates is a function of the resin content.

Normally, the resin content of a glass fiber-polyester laminate is determined by igniting the specimen at 565 $\pm 27.5°C$ until the resin is vaporized and driven off. The difference in weight between the original specimen and the ignition residue is thus equal to the original resin content. However, calcium carbonate is known to dissociate into calcium oxide and carbon dioxide at temperatures above 525°C. Thus, if calcium carbonate is present in a laminate specimen, carbon dioxide is drawn off during the test, and ignition loss is actually greater than the amount of resin in the specimen.

In the Bureau method, the laminate specimen is first ignited until there are no further changes in weight. The ignition residue is treated with an excess of saturated ammonium carbonate solution, which reacts with calcium oxide to form calcium carbonate. The treated residue is then placed in a constant-temperature oven at 80°C in order to decompose and remove any unreacted ammonium carbonate. After this treatment the ignition residue contains the same amount of calcium carbonate as the original specimen, so that the resin content can be calculated by difference.

In the course of the investigation, the Bureau determined the effect of ignition at high temperatures on three control groups of plastic-laminate specimens in order to determine whether the suggested test modification would correct the source of error. The materials used were an unsaturated polyester resin, precipitated calcium carbonate filler, and unoriented glass fiber mat. The specimens were divided into three groups. Specimens in group A contained resin and glass fiber only; groups B and C contained resin, glass fiber, and calcium carbonate. The ingredients were weighed into a porcelain crucible on an analytical balance. The proportions chosen are convenient experimentally and similar to those used in commercial laminates. The specimens in group A contained equal parts of resin and glass fiber, by weight. Those in groups B and C contained 4 parts resin, 3 parts glass fiber, and 1 part filler, by weight. All specimens weighed 3 grams.

After curing, the specimens were placed in a muffle furnace and ignited at 565°C for 1½ hours. The ignition loss for the group A specimens was less than 51 percent of the original specimen weight, but the losses in groups B and C were over 54 percent. These values were corrected for the volatile fiber finish on the glass fibers, previously determined on samples of glass mat, giving groups A, B, and C 50.01, 53.48, and 53.83 percent corrected ignition loss values, respectively.

The ignition residues of group B specimens were then treated with ammonium carbonate, as were those in control group A. The specimens from group A (which contained no calcium carbonate) showed little change in weight—less than one-tenth of a percent. But group B showed an increase of 3.4 percent. Control group C containing filler was treated no further. The end weights of all three groups were then compared to the original weights of the specimens. The differences between resin contents as determined by test and the known original resin contents were −0.05 percent for group A, 0.01 percent for group B, and 3.75 percent for group C (table 1).

The Bureau's findings are evidence that dissociation of calcium carbonate is a source of error when the usual test for resin content is applied to glass fiber-polyester-calcium carbonate laminates. The suggested test using ammonium carbonate quantitatively corrects the errors and is rapid and accurate. The reduction of error in resin-content tests from 3.5 to about 0.01 percent may prevent rejection of certain laminates otherwise meeting specifications.

For further details, see Determination of resin content of glass fiber-polyester laminates containing a calcium carbonate filler, *by S. D. Toner, Anal. Chem. (in press).*

TABLE 1. *Resin content determination, average values* [a]

Group	Loss of weight on ignition	Fiber finish	Corrected ignition weight loss [b]	Carbon dioxide absorbed [c]	Measured resin content [d]	Original resin content	Difference in resin content: measured less original
(*wt %*)	*wt %*	*wt %*	*wt %*	*wt %*	*wt %*	*wt %*	*wt %*
A (50.00 resin, 50.00 glass fiber)	50.76	0.75	50.01	0.07	49.95	50.00	−0.05
B (50.07 resin, 37.43 glass fiber, 12.50 CaCO₃)	54.04	.56	53.48	3.40	50.08	50.07	.01
C (50.08 resin, 37.41 glass fiber, 12.51 CaCO₃)	54.39	.56	53.83		53.83	50.08	3.75

[a] All values given are average for the group and are based on the original weights of the specimens.
[b] Loss of weight on ignition less fiber finish. Results obtained by normal method of determining resin content.
[c] Increase in residual weight after treatment with ammonium carbonate.
[d] Corrected ignition weight loss less amount of carbon dioxide absorbed.

Determination of Minor Constituents of Zinc Alloys

AN ELECTROLYTIC procedure has been developed for precise determination of very small amounts of impurities in zinc and zinc-base alloys. The procedure does not require preliminary chemical separations, is relatively fast, and requires little operative attention. It should also be useful for analysis of other metals as well as zinc, particularly nonferrous alloys. Developed by J. K. Taylor and S. W. Smith of the physical chemistry laboratory, the method makes use of electrolysis at controlled potential, a technique that is finding increasing use in selectively separating the metallic constituents of a solution.[1] Unlike previous methods, the procedure deposits the metals in a mercury cathode from which they are selectively removed by anodic dissolution for quantitative determination.

Zinc is one of the more important metals commercially: sheet metal products are galvanized with spelter

increases the test sensitivity, the small volume of solvent used limits the size of the sample that can be tested.

In the method developed by the Bureau, the sample is dissolved in an electrolyte and placed in an electrolytic cell. A mercury-pool cathode in the base of the cell is connected through a stopcock to a mercury reservoir. The anode is a platinum gauze cylinder inserted at the top of the cell. The solution to be analyzed is electrolyzed at a potential that allows zinc to remain in the electrolyte but withdraws copper, tin, lead, and cadmium into the mercury pool. When electrolysis is complete, the residual zinc solution is discarded and replaced by a fresh electrolyte. Electrolysis is then resumed at a lower potential chosen to redissolve the trace elements, singly or collectively, from the mercury. The solutions obtained are then analyzed polarographically with no interference from zinc.

Electrolysis cell with a mercury cathode at controlled potential used to analyze a zinc alloy solution. Cell anode is a platinum gauze cylinder. Motor-driven stirrer minimizes concentration-polarization effects at solution-mercury interface. Potentiostat (left) automatically maintains cathode potential with respect to calomel reference electrode (dipping into solution). Platinum contact (drawing) for the mercury cathode is as close as possible to the drain stopcock and thus maintains electrical connection until all of the mercury is drained.
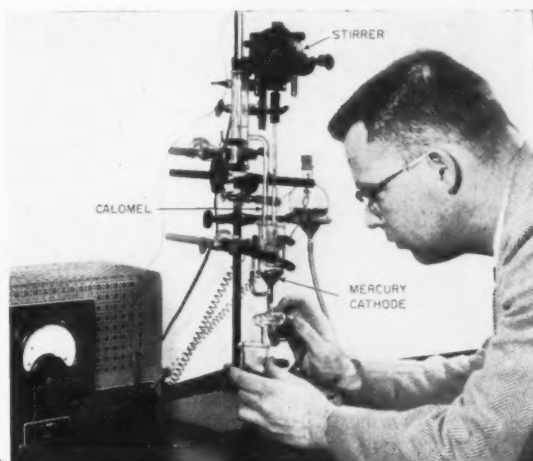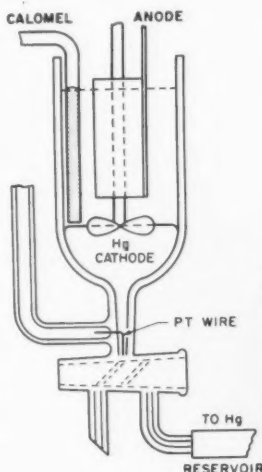
(99 percent zinc); zinc-base diecasting alloys have the advantages of low cost and low melting point. Thus industry as well as science is interested in the physical properties of zinc alloys. These properties are a function of alloying and trace metals like copper, lead, tin, and cadmium. Generally, the presence and quantities of such metals in zinc alloys are conveniently and accurately determined by polarographic analysis—a method based on interpretation of current-voltage curves obtained during electrolysis of an alloy solution. However, copper and zinc, when present in relatively large quantities, interfere and cause inaccuracies in the results. Conventional polarographic methods are limited, even for alloys of very low copper content, when small amounts of other trace metals are to be determined. In such cases, the sample of the alloy to be tested is usually dissolved in a minimum volume of solvent so as to insure maximum concentration of trace elements in the test solution. Although this procedure

This method of separating the metal constituents by means of a mercury-pool cathode increases the sensitivity and precision of polarographic determinations and eliminates the difficulties of previous methods. The present method has been used to determine lead and cadmium in zinc-base diecasting alloys to be used in NBS Standard Samples for spectrographic analysis. Lead and cadmium contents thus determined ranged from 0.0006 to 0.010 percent when copper contents were as much as 1.5 percent. The results obtained polarographically are in excellent agreement with those obtained by cooperating laboratories using more elaborate methods.

[1] For further technical details, see Polarographic determination of lead and cadmium in zinc-base alloys using electrolytic separations at controlled potential, by J. K. Taylor and S. W. Smith, J. Research NBS 56, 301 (1956) RP2679.
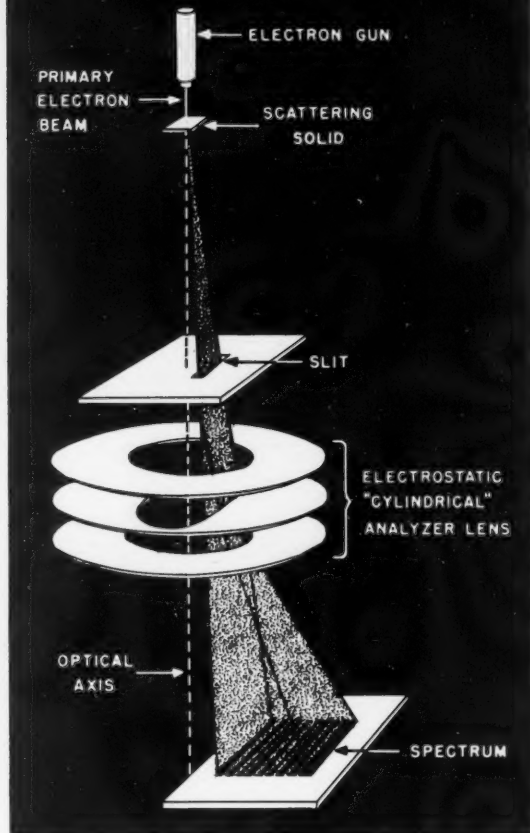
LOW-ENERGY ELECTRON SCATTER

IT HAS BEEN known since 1926 that when electrons of relatively low energy (less than 150 kev) strike a solid surface, some of the scattered electrons lose energy in small amounts that are characteristic of the solid. The same result, a kind of line spectrum of energy loss distribution, is obtained when the electrons are scattered by passage through thin layers of a solid. Although a number of investigations of the effect have been reported in the last quarter-century, considerable uncertainty remains in regard to both the experimental findings and their theoretical interpretation. Much greater attention, in fact, has been directed to the scattering of high-energy electrons, with interest centered on interactions with nuclei.

Seeking a better understanding of low-energy scattering, the National Bureau of Standards has been conducting a systematic exploration of this phenomenon.[1] The program, now in its fifth year, has been directed by L. Marton, chief of the electron physics laboratory. L. B. Leder, T. F. McCraw, H. Mendlowitz, and J. A. Simpson have conducted much of the research; and, more recently, U. Fano, chief of the nuclear physics laboratory, has contributed theoretical analyses. The program is supported by the Office of Naval Research, the Atomic Energy Commission, and the Bureau.

Using electron beams in the range, 0 to 150 kev, the Bureau experiments have concentrated on the scattering losses below 100 ev due to single inelastic collisions. Multiple collisions may be avoided almost completely by using sufficiently thin scattering specimens. So far, there has been progress in several directions: Experimental technique and instrument design have been improved, data have been obtained on a great many scattering materials, and a number of theoretical studies have been made.

Systematic study of electron scattering is expected to provide information needed in many other fields. First of all, it should throw light on many problems in solid-state physics. The well-known applications of solid-state physics to semiconductors and transistors were achieved with only a minimum experimental basis. Thus the results of electron scattering studies should not only strengthen solid-state theory but may well add considerably to its practical potential.

Perhaps equally important is the application of scattering data to the study of radiation effects. This is of as much interest in medicine and biophysics as it is in fundamental physics. Most radiation, such as X-rays, does not act directly, but rather by way of the electrons released in matter. Hence, when the action of the individual electron in a single collision is more adequately known, a better picture can be formed of the total effect of the radiation under investigation.

The study also bears directly on problems in electron optics. In the electron microscope, for example, the primary process of image formation is the scattering of electrons in the specimen. If this process introduces differences in the velocities of the electrons, "chromatic" aberration results. This problem served as the impetus for the Bureau's program of quantitative studies of scattering. Still another phenomenon that may be clarified by electron scattering studies is secondary electron emission, which is essential to the op-
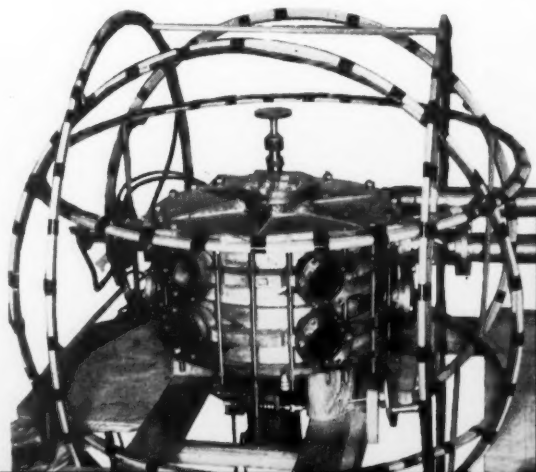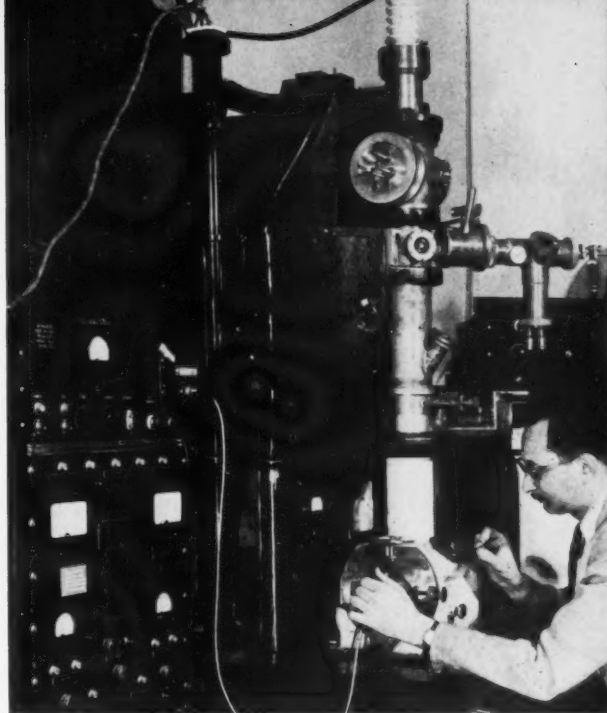
eration of many types of vacuum tubes. Here the new data may add much to the interpretation of observed effects and development of better instrumentation.

instrumentation

Two principal instruments have been used in the Bureau experiments, and a third has just been constructed. The first resembles an electron microscope. Based on the method of velocity analysis introduced in 1949 by G. Möllenstedt, it has an energy resolution of 1 part in 30,000 and is used to study electrons scattered within a small angle (10^{-7} steradian) about the primary beam direction.

In the original design, an electron gun sends the primary beam down towards a thin film of specimen. Passing through, the scattered electrons are focused by an electrostatic objective lens into an image on an opaque screen. A slit in the screen allows part of the image to be magnified by a cylindrical lens, the analyzer. If the electrons all had one velocity, or the analyzer were free of chromatic aberration, a single image of the slit would be formed. However, if the slit is moved away from the optical axis, the chromatic aberration will be greatly increased. The result is a spectrum, with separate images of the slit corresponding to the different velocities of the electrons. The spectrum falls on a photographic plate and a micro-

densitometer is used to determine the energy distribution.

In the Bureau's version of this instrument, two major improvements were made. It was found, first, that the precision of intensity measurements could be increased by replacing the photographic plate with another kind of detector. This is a fluorescent layer connected by a light pipe to a photomultiplier. As only a narrow segment of the spectrum may reach the detector at one time, energy scan is produced by varying the analyzer lens potential and recording simultaneously the output of the photomultiplier. The other change eliminates errors due to chromatic aberration in the objective lens by inverting the positions of objective lens and specimen. With this arrangement, the objective is not used during actual scattering experiments. It is often convenient, however, to be able to examine an enlarged image of the specimen. To do this, the objective is switched on and a highly reduced image of the electron source is formed just above the specimen. This image, in turn, projects an enlarged shadow image of the specimen on the slit plane.
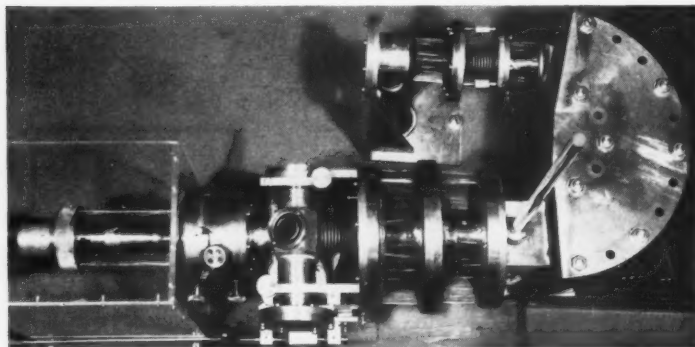
In this and in the other electron-optical instruments designed by the Bureau, an effort is made to use a fixed, well-determined value for the solid angle subtended by the analyzer entrance. A survey of previous work in the field showed that this angle was often defined either poorly or not at all. As Bureau studies indicate that the angular distributions for elastically (i. e., with zero loss) and inelastically scattered electrons are quite different, it is clear that investigators using different acceptance angles will obtain different relative intensities and spectral line shapes for the two kinds of electrons.
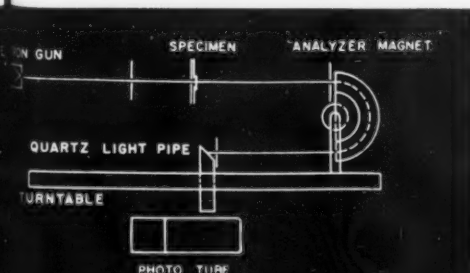
A second instrument was designed by Bureau scientists in order to investigate scattering at angles up to 150° from the forward direction of the primary beam. Though having a resolution of only 1 part in 2,000, it is adequate for many purposes. In particular, it made possible the first extensive study of the angular distribution of scattered electrons and gave information about the relation between angle and relative intensities of energy spectrum lines. Measurements with this instrument on a single specimen are conveniently summarized in a cartographic plot (fig. 3). In this representation, angle is the abscissa and energy loss in electron volts is the ordinate. The third coordinate, intensity, is shown by contour lines of equal intensity. Use of a quasi-logarithmic sequence of contours permits compact coverage of an intensity range of 4 to 6,000.

In the large-angle instrument, scattering occurs inside a cylindrical vacuum chamber 36 cm in diameter and 18.5 cm high. The specimen is inserted through a port in the top and can be manipulated from the outside. It can also be electrically heated to reduce the rate of specimen contamination to a low level. An electron gun projects radially into the chamber, point-

Once the instrument is put into operation, with the analyzer set at a given angle with the primary beam, an energy loss spectrum is automatically recorded. The turntable then shifts by 0.00058 radian and the same cycle is repeated every 2 sec until the maximum angle is reached.

The two instruments described have yielded and are yielding important data. Nevertheless, greater resolution is required if, for example, the suspected fine structure of scattering loss spectra is to be detected. The relatively undeveloped state of the technique is suggested by the resolution of 1 part in 100,000,000 attained in light spectroscopy. By contrast, the best electron spectrometers in use at the present time can probably not exceed 1 part in 70,000. A very promising approach to higher resolution, Bureau studies indicate, is the use of a decelerating field preceding a magnetic analyzer. An instrument of this kind has therefore been constructed and preliminary trials of its operation are under way.

In this instrument, a Siegbahn-type magnetic analyzer is used which, by itself, provides a resolution of 1 part in 1,000. However, if scattered electrons with an average energy of, say, 50 kev, can first be decel-

New instrument for studying energy distribution of electrons scattered by thin solid films. Just completed, it is expected to show a marked improvement in resolving power over older instruments (seen from above).

ing towards the specimen. Scattered electrons enter a slit in a magnetic analyzer, are deflected into a semicircular path by a magnetic field, and leave through another slit in the analyzer. The emerging electrons move back towards the axis of the chamber, their directions nearly reversed by the analyzer.

Only electrons entering the analyzer with energy falling within a certain narrow range will reach the exit slit. Those with higher energy, for example, will be deflected along a less curved path, and so will be stopped by the analyzer wall; by increasing the magnetic field intensity these higher-energy electrons may be made to pass through the slit instead of those that did so before. Thus energy scan is obtained by varying the magnetic field.

From the analyzer the electrons proceed towards the detector, which again is a fluorescent layer, and light generated in the layer by electron impact is guided by a quartz light pipe to a photomultiplier just below the chamber. The analyzer and detector are mounted on a turntable that rotates about the chamber axis.

erated to an average of 100 ev without distorting the energy profile, an over-all resolution of 1 part in 500,000 can be obtained. Also, once the electrons leave the analyzer, they may be accelerated to the extent needed to give a strong indication on the detector.

some quantitative results

A great many substances, elementary and compound, have been measured with the modified Möllenstedt instrument. Generally, substances that could be prepared in the form of a self-supporting foil were investigated as such. Otherwise, supporting substrates were used.

For the alkali metals, the Bureau's values are the only ones available. They were taken by distilling a thin layer of the metal onto a supporting film (collodion or SiO_2) in the vacuum of the scattering instrument. The vacuum was not very high—of the order of 2×10^{-5} mm of mercury—but high enough to prevent rapid oxidation of the metal.

The results here are complicated by the fact that the spectra of the supports are superposed on those of the substance under study. Also, it is not always possible simply to deduct the substrate lines. Strangely enough, the substrate spectrum seems to be modified when certain metals are applied to it. Whether this may be explained by diffusion of metal into the substrate remains to be shown.

Attention was next given to compounds. A number of simple compounds were measured that show the same type of spectrum for both element and compound, except that the whole spectrum is shifted towards higher energy values for the compound. Table 1 summarizes some of these results; it lists energy losses (ΔE) corresponding to two or three loss-spectrum lines. A similar shift had been noted in the case of X-ray absorption limits, and several explanations were proposed. K. Das Gupta attempted to relate shifts in the spectra of the components of a compound with the heat of formation. On applying Das Gupta's formula to the case of electron losses, it was found to give the correct order of magnitude and direction of shift, but not much more. The best agreement between calculated and observed values was obtained with the lowest values of ΔE for the sulfides and with the highest values of ΔE for the oxides.

In experiments with the large-angle instrument, most attention was given to gold. For some of these experiments a film of the substance, 100 A thick, was prepared in the form of a single crystal. As the energy resolution of this instrument is not as good as that of the small-angle instrument, the characteristic energy loss for gold (24 ev) is barely indicated at zero angle by a slight asymmetry in the energy spectrum (fig. 2). At an angle of 0.0058 radian with the primary beam, however, almost all the intensity appears at 24 ev. At still larger angles, for instance at 0.04 radian, the intensity distribution has two peaks, one for the elastic event and the other for the inelastic one. If intensities are plotted against angle for both zero-loss and 24 ev-loss electrons (fig. 1), it is again seen that the probability for the elastic event is much larger than for the 24-ev inelastic one at zero angle. The ratio changes very rapidly, however, and at 0.005 radian the two curves cross over. Then the intensity of the characteristic loss exceeds that of the elastic event until the curves cross again at around 0.042 radian, just before a diffraction maximum. As might be expected, zero-loss electrons predominate at that angle. There is also an increase in the number of inelastically scattered electrons due to double collisions. The cartographic plot (fig. 3) provides still another representation of these results.

After gold had been studied, to some extent, as representative of the heavy elements, attention was turned to the beginning of the periodic system. In the case of beryllium, the most surprising feature of the scattering distribution is that the inelastic cross section is rather high at the diffraction maxima. Also, for reasons not yet clear, it is not the first and most intense characteristic line of Be at 20 ev that appears in the diffraction processes, but a higher energy loss. Aluminum, on
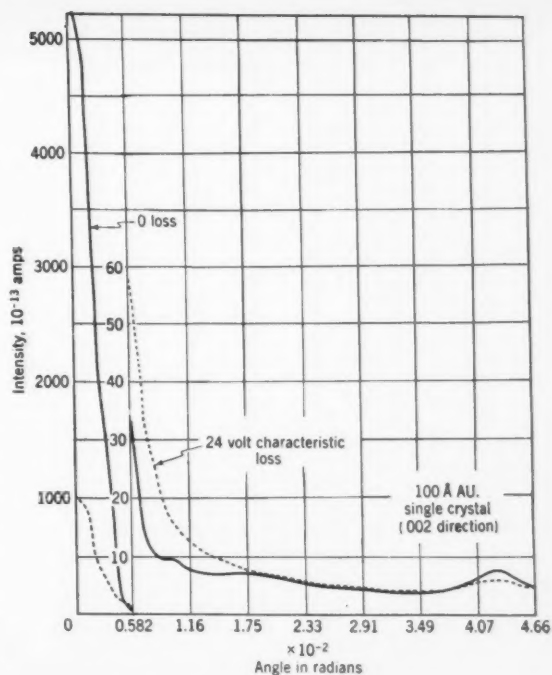

FIG. 1

Above: Angular distribution of elastic (zero-loss) and characteristic loss intensities for single-crystal gold obtained with the wide-angle analyzer. *Below:* Energy distributions of electrons scattered at several fixed angles by a single-crystal gold film, as measured by wide-angle scattering analyzer. (Drawings courtesy Academic Press.)
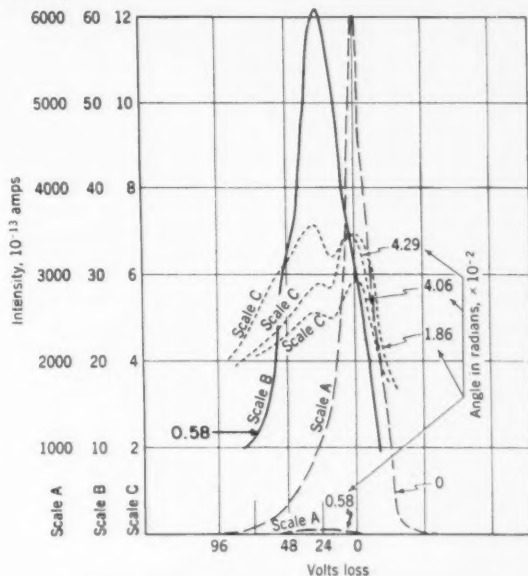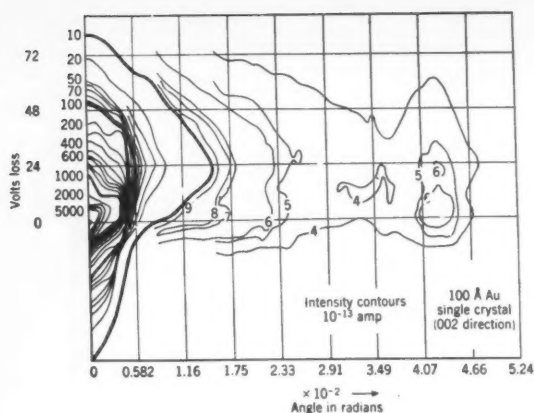
FIG. 2

FIG. 3

Volts loss: 72, 48, 24, 0
10, 20, 50, 70, 100, 200, 400, 600, 1000, 2000, 5000

0   0.582   1.16   1.75   2.33   2.91   3.49   4.07   4.66   5.24

× 10⁻² ⟶
Angle in radians

Intensity contours 10^{-13} amp

100 Å Au single crystal (002 direction)

Cartographic presentation of data obtained with large-angle scattering analyzer, showing angular and intensity distribution of electrons scattered by a thin crystal of gold. Contours represent points of equal intensity. Note that the change in intensity from one contour to the next is not a fixed amount, but varies in accordance with the quasi-logarithmic scale shown just left of the graph. (Drawing courtesy Academic Press.)

the other hand, shows a very well marked centering of the most important diffraction maximum on the zero loss line. (The Al data are also interesting because of the very steep decline in intensity close to the zero angle, with a thousand-to-one drop within an angle of 0.002 radian.)

comparisons with theory

In addition to obtaining new data on electron scattering, Bureau scientists have examined the bearing of these results (and those obtained elsewhere) on the various theories that have been proposed. It is believed that some advances have been made in clarifying the problem and in working out partial solutions. Pending closer comparison with the most recent results of other laboratories, these must be regarded as tentative.

Among the theories considered is the so-called plasma theory of Bohm and Pines, which has had considerable success in solid-state physics. In its first version, the conduction electrons of a metal are treated as a Fermi gas which is embedded in a smeared-out medium of fixed positive charge and is excited to collective oscillation by incoming electrons. The theory has the virtue of simplicity, is easy to compare with experiment, and has suggested directions of further research. Nevertheless, it meets with serious difficulties, and these have not yielded to any of the simpler modifications of the theory that seem possible. For example, it predicts only a single energy loss, but more than one is the general rule. As long as these losses are integral multiples of a single value, multiple collisions could be invoked if the theory could properly explain the minimum loss. Yet in many cases the loss lines are not multiples of a single value.

Another serious drawback is that the collective oscillation description cannot account for lines observed in insulators and in metal compounds. Attempts have been made to apply some of the methods of the collective oscillation description to nonconducting media, using an essentially semiclassical treatment of the dielectric. The outlook becomes more promising, however, when a quantum-mechanical analysis of the dielectric constant is made. On the basis of this analysis, the plasma theory can be considered a special case of a broader problem. It is then possible, by employing the quantum-mechanical treatment as a guide, to utilize the semiclassical formula in connection with experiment to obtain needed information on oscillator strengths.

Another approach to the problem of electron scattering losses is to compare them with X-ray absorption spectra. The K-, L-, and other absorption edges are known to shift when an element is replaced by a compound of that element. The work of Das Gupta in this connection has been mentioned above. It is more or less reasonable, therefore, to try to correlate the fine structure of these absorption edges, as well as the fine structures observed at the short wavelength limits, with the characteristic energy losses. A number of attempts in this direction had already been made. At the Bureau, a comparison of this sort was made for the nearly 20 elements and compounds for which the two kinds of data were available, using roughly averaged values for characteristic losses obtained in different laboratories. A high degree of agreement was found.

The search for a physical basis for this result led back to the first attempts to explain electron characteristic losses made by Rudberg, Slater, and Haworth 20 years ago. In that interpretation, the observed energy losses are supposed to be caused by excitation of conduction electrons to higher energy levels. These levels are not those of the individual atoms, but are associated with the crystal structure of the solid. This theory is thus another sort of "collective" explanation, but one that takes the specific crystal structure into account. It was used by Slater and Haworth to estimate an energy distribution curve for copper, but only a rather limited agreement with measurements was found.

Subsequently, it appeared that experimental difficulties were largely responsible for the latter result. With better techniques, measured and calculated values moved steadily closer. On reconsidering the explanation advanced by Rudberg, Slater, and Haworth in the light of the comparison of X-ray and electron data, it was necessary to assume that the characteristic losses, in many cases at least, represent an interband transition from the "Fermi sea" to the bands above. This is easily acceptable wherever the width of the characteristic line is comparable to that of the Fermi sea. Transitions may then be assumed to take place anywhere within that band. When the observed line is sharper than the width of the Fermi sea, as for Al and possibly also Be and Mg, the loss may be ascribed

to the excitation of collective oscillations in the electron plasma. The quantum-mechanical treatment mentioned above indicates that for these elements the plasma interaction should be very strong.

An alternative explanation for the case of narrow lines has recently been suggested by T. H. Berlin of Johns Hopkins University. As the momentum change in these phenomena is small, it may be assumed that only those transitions are allowed that have small angular momentum changes, e. g., $L=0,1$. By expressing the distribution function of the Fermi sea in terms of angular momentum about the direction of the incident electrons, it may be possible to find a well defined stratum giving rise to a sharp transition line. At present, however, much more work, both experimental and theoretical, is needed to decide the issue.

plans for further research

Current plans call for continuation and extension of the electron-scattering studies. One important project for which preparations have been made is the study of scattering by metallic vapors. If the energy loss spectrum of a metallic vapor is the same as that of the solid metal, this would indicate that the collision process involves individual atoms of the scatterer. If the spectra are different, support would be obtained for theories that assume interaction between the electron and the scattering atoms as a collective whole. Modifications of the small-angle instrument have already been made for this purpose.

It is hoped shortly to apply the predeceleration instrument to a reexamination of the solid films already measured with other instruments as well as to the study of additional solids. Large-angle scattering measurements will continue on a greater number of substances

as guided by theoretical results. Meanwhile, theoretical investigations of energy-loss phenomena will be conducted in parallel with the experimental activities.

TABLE 1. *Comparison of characteristic energy losses* (ΔE) *in elements and compounds as measured in electron-scattering experiments*

Subscripts indicate different loss-spectrum lines.

Material	Energy loss (ev)		
	ΔE_1	ΔE_2	ΔE_3
Si	4.8	16.9	
SiO₂	5.4	19.4	
Te	4.6	16.0	
TeO₂	9.5	17.5	
Pb	5.1	12.1	21.8
PbS	6.8	14.7	21.9
Sb	4.3	14.9	30.6
Sb₂S₃	6.3	18.0	35.4

[1] *For further technical details, see* Energy loss of electrons in passage through thin films, *by* L. Marton and L. B. Leder, Phys. Rev. **94**, 203 (*Jan.* 1954); Effect of chemical combination on the characteristic energy loss of electrons, *by* L. B. Leder and L. Marton, Phys. Rev. **95**, 1345 (*Sept* 1954); Distribution of electrons scattered by gold, *by* L. Marton, J. A. Simpson, and T. F. McCraw, Phys. Rev. **99**, 495 (*July* 1955); Automatic instrument for electron scattering measurements, *by* L. Marton, J. A. Simpson, and T. F. McCraw, Rev. Sci. Instr. **26**, 855 (*Sept.* 1955); Comparison of the characteristic energy losses of electrons with the fine structure of the X-ray absorption spectra, *by* L. B. Leder, H. Mendlowitz, and L. Marton, Phys. Rev. **101**, 1460 (*Mar.* 1956). *Electron scattering studies at the Bureau and at other laboratories are reviewed by* L. Marton, L. B. Leder, *and* H. Mendlowitz *in* Advances in electronics and electron physics, Vol. VII, *edited by* L. Marton, pp. 183–238 (*Academic Press*, 1955).

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RP2672. Characteristics of an image-forming system. Roland V. Shack.

RP2673. Advances in the design and application of the radiofrequency permeameter. Alvin L. Rasmussen, Albert W. Enfield, and Alfred Hess.

RP2674. A new computer for calculating the water content of gases. A. W. Diniak and E. R. Weaver.

RP2675. Vibrational constants of acetylene-d₂. Harry C. Allen, Jr., L. R. Blaine, and Earle K. Plyler.

RP2676. Heat capacity of polyisobutylene from 0° to 380°K. George T. Furukawa and Martin L. Reilly.

RP2677. Preparation of barium titanyl oxalate tetrahydrate for conversion to barium titanate of high purity. W. Stanley Clabaugh, Edward M. Swiggard, and Raleigh Gilchrist.

RP2678. A five-band recording spectroradiometer. C. S. McCamy.

RP2679. Polarographic determination of lead and cadmium in zinc-base alloys, using electrolytic separations at controlled potential. John K. Taylor and Stanley W. Smith.

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C566. Bibliography of solid adsorbents. Victor Deitz. $8.75.

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Patents

(The following U. S. Patents have been granted to NBS inventors. Assigned to the United States of America, as represented by the Secretary of the Department noted in parentheses.)

No. 2,734,276. February 14, 1956. Development of technique for high temperature stress-strain measurements. Preston R. Weaver. (Navy).

No. 2,738,412. March 13, 1956. Compass illuminating assembly. Nye S. Spencer, Alvin G. McNish, and Hugh F. Gingerich. (Navy).

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No. 2,738,591. March 20, 1956. Ship's magnetic compass. Nye S. Spencer, Alvin G. McNish, and Hugh F. Gingerich. (Navy).

No. 2,739,032. March 20, 1956. Iron-catalyzed decomposition of sodium chlorite. William K. Wilson. (Commerce).

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